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NASA TECHNICAL TRANSLATION

NASA TT F-15,354

CHARACTERISTIC LINES (YEARLY PERMANENT LEVEL LINES) AND CHARACTERISTIC WIND VARIABLES FOR WIND ENERGY PRODUCTION

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(NASA-TT-F-15354) CHARACTERISTIC LINES (YEARLY PERMANENT LEVEL LINES) AND CHARACTERISTIC WIND VARIABLES FOR WIND ENERGY PRODUCTION (Scientific Translation Service) ~~25~~ 2 p HC $3.25 CSCL 10B

N74-15747

Unclas G3/03 29019

Translation of: "Kennlinien (Jahresdauerlinien) und Kenngrössen des Windes für die Windkraftnutzung". Elektrizitätswirtschaft, Vol. 54, No. 20, October, 1955, pp. 704-709.

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546 FEBRUARY 1974

CHARACTERISTIC LINES (YEARLY PERMANENT LEVEL LINES) AND CHARACTERISTIC WIND VARIABLES FOR WIND ENERGY PRODUCTION

Hans Pigge*

We believe that the following article will be very important /704** for evaluating wind power generation for supplying electrical energy. Important variables are derived for the design power level and the yearly energy based on the yearly permanent level lines. The article gives us an idea of what is contained in the wind (the publishers).

B. Koetzold, Director of the electrical plant, Wesertal GmbH, Hameln, has considered the international importance of wind power production for the electrical economy. He has suggested *** that characteristics for the wind be prepared in the form of yearly permanent level lines. This is to be done for the specific raw wind power (kW/m^2) and for the specific yearly raw wind energy

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* Hameln. Lecture held at the Wind Generation Meeting at Oldenburg 1.0. on May 13, 1955.

** Numbers in the margin indicate pagination of original foreign text.

*** Discussion of the lectures by K. Schneider-Carius, meteorological considerations for exploiting air flows for the purpose of wind power production and W. Caspar, evaluation of the wind data for wind power generation in Germany, Communication No. 4 of the Wind Generation Study Group, Stuttgart, 1955. Other publications of the study association are given on Page II of this issue.

(in kWh/m^2). These so-called permanent level lines are derived from the wind velocity permanent level lines [1] of a windy location and are especially important for optimum performance design. This is closely related with the available net yearly energy and the economy of the installation, i.e., the net costs per kilowatt hour. Similar calculations are performed for hydroelectric power.

The author has taken up this suggestion, i.e., the mentioned permanent level lines have been drawn for three characteristic wind locations (measurement stations of the German Weather Service) based on the "Wind Data" *. This refers only to the raw values for wind power and yearly wind energy which is contained in the wind and which refers to one m^2 of area F_R. The absolute magnitudes can be obtained from the specific raw values by multiplying them with the wheel area F_R (m^2), the working characteristic variables (power coefficient C_1 and total efficiency η) and the exploitation degree Σp, to be defined later on.

A number of basic relationships were discovered when these permanent level lines were established. These give a relatively simple overview of wind conditions which is why we would like to discuss them here.

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* Data for distribution of wind velocity in Germany for wind power generation, written by the Climate Division of the German Weather Service, Bad Kissingen, at the request of the Wind Power Generation Study Group, e. V., Stuttgart. Author W. Caspar, Communication No. 3 of the Wind Generation Study Group, Stuttgart, 1954.

I. CHARACTERISTICS (YEARLY PERMANENT LEVEL LINES)

The investigation was restricted to three measurement stations, which are examples for low, medium and high average wind velocity V_m:

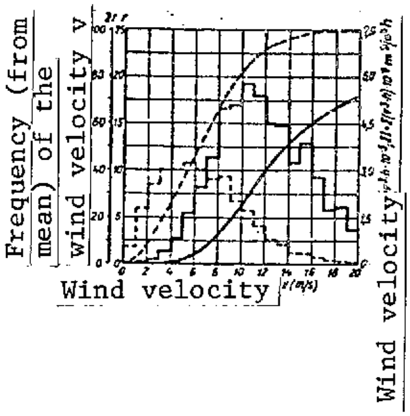
Altenwalde-Cuxhaven	$v_m = 4.37$ m/s.
Helgoland	$v_m = 6.66$ m/s.
Brocken	$v_m = 10.12$ m/s.

Figure 1 shows the characteristic drawing for the Helgoland Station in the representation of "wind data". The dashed, step line is the average wind frequency (wind velocity) over a year, i.e., the percentage of hours over the year which the wind velocity indicated on the abscissa occurs (intervals of 1 m/s). The dashed curve is the sum curve of the frequency distribution. If we also form the arithmetic mean of the third power of the interval velocity from v_n to v_{n+1}, corresponding to the dependence of the wind power or the wind energy on the third power of wind velocity v, that is

$$\bar{v}^3 = \frac{v_n^3 + v_{n+1}^3}{2} \qquad (1)$$

and if we multiply with the absolute magnitude of the corresponding yearly hours, then we obtain a numerical value J proportional to the wind energy of the v intervals having the dimension $m^3s^{-3}h$. These magnitudes J are shown by the solid step curves as a function of wind velocity. The solid curve gives the sum curve of the energy intervals. The final value of the energy sum curve represents the yearly raw power energy ΣJ of the wind location. It is as follows for the three stations:

Altenwalde-Cuxhaven	$2.1 \cdot 10^6\ m^3 s^{-3} h$	($v = 0 - 20$ m/s)
Helgoland	$5.5 \cdot 10^6\ m^3 s^{-3} h$	($v = 0 - 25$ m/s)
Brocken	$16.8 \cdot 10^6\ m^3 s^{-3} h$	($v = 0 - 35$ m/s)



Station altitude above sea level 56 m, transducer 21 m over the ground, time period 1935/1936 and 1939.

Figure 1. Example for wind evaluations according to the "wind data" (Helgoland Station)

This representation has the advantage that from it the energy magnitudes corresponding to the individual v intervals can be read off directly or by forming differences. In addition, all variables can be represented over the entire v range with about the same absolute accuracy. However, often it is desired to have a direct relationship between time and the corresponding power and energy input, which makes it necessary to make a calculation involving the wind velocity. In addition, for energy purposes, it is also of interest to know the power and energy magnitudes on a kW or kWh scale contained in the wind, which is why it is important to draw the so-called permanent level lines. It seems appropriate to first define the permanent level line. According to the "concept definitions for energy industry" [2], a "permanent level line is a conversion of a variation line with respect to magnitude over a time interval." The variation line represents the variation of the variable over time. The permanent level line can be used to determine how long the maximum value of the variable occurs as well as its components over the time interval under discussion. Figure 2 shows an example of the permanent level lines for the outflow permanent level lines of the Weser River for the year 1954 (in addition to other numerical data and not of interest here). This is an /705

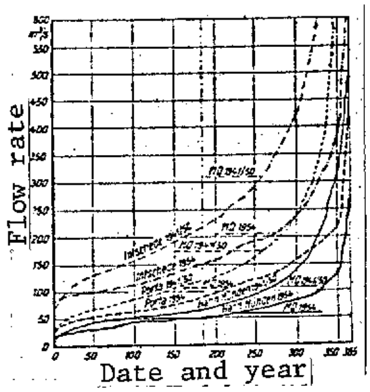


Figure 2. Official representation of the flow rate lines (Weser flow region, 1954)

official representation by the water and shipping administration. The time axis is divided into days. Because of the small daily fluctuation of the rivers, this results in a sufficient accuracy. We would like to mention that this is not the representation of the permanent level line usually given in the electrical industry. Usually the maximum values are on the left, but here the maximum values are on the right. The difference is not important. In the electrical industry, when for example the maximum load or the heat consumption of a steam generation plant is represented, usually we are interested in limited maximum values (capacity). In the water power generation industry (also in the wind power generation industry), the maximum values are statistical average values and their values cannot be determined uniquely .

Figure 3 shows the yearly permanent level lines of the wind for the measurement station Helgoland. The following are plotted on a relative and absolute scale (hours) along the time axis:

1. The wind velocity v (in intervals of n = 1 m/sec).

2. The specific raw wind power L_o (in kW/m^2), calculated

according to the relationship

$$L_o = 6{,}14 \cdot 10^{-4}\, v^3 \left(\mathrm{kW/m^2}\right) * \qquad (2)$$

where v^3 is the arithmetic mean according to Equation (1), in accordance with the "Data".

3. The specific raw energy W_o (in k Wh/m^2) of each v interval and to n + 1.

4. The specific yearly raw wind energy ΣW_o (in kWh/m^2) (from the sum of W_o values). This energy sum ΣW_o therefore represents approximately the area under the L_o curve, that is

$$\Sigma W_o = \int_0^{\infty} L_o(v)\, dt(v) \text{ (in kWh/m}^2) \qquad (3)$$

if dt is the time interval in hours corresponding to each v interval n to n + 1.

These four permanent level lines give an accurate description of the wind variation at a windy location. All the parameters derived from the wind velocity v were reduced to unit area swept out by the wind, in order to obtain universal variables. This was already mentioned.

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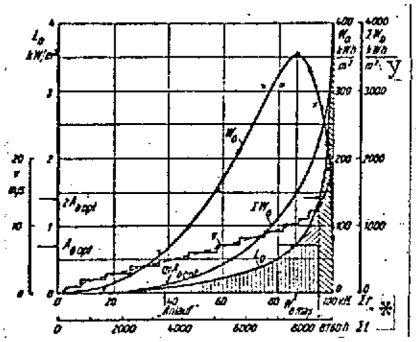
* This relationship is obtained for the performance formula for a wind wheel $L = \frac{F_R \cdot v^3 \cdot \varrho}{2 \cdot 102}$ (kW) with a power coefficient c_1 = 1 air density of $\varrho = 0.125$ for 15° C and a wheel area of F_R = 1 m^2. The The power L_o is the raw power level for 1 m^2 of wind passage area.



Measurement height above nominal sea level H_N = 77 m, measurement above ground H_G = 21 m

v_m = 6,66 m/s, $A_{o\,opt}$ = 0,70 kW/m² at v_E = 10,4 m/s, $\sum W_o$ = 3340 kWh/m², $\sum_{P_{max}}$ = 55,2 v. H., $\sum_{z_{max}}$ = 56,3 v. H.

Figure 3. Yearly duration lines of the wind for average wind velocity v_m (Helgoland)

Translator's note: Illegible in foreign text.

The variation of the characteristic variables shows that only the W_o curve has a maximum. This is a natural law which can be formulated as follows: in any time-dependent frequency distribution of a statistical variable with uniform intervals, there is a region which contains the maximum value of the time function of the static variable (energy). It is natural to establish a correspondence between this energy maximum and the so-called design power level when wind power generation is discussed. This design power level produces the maximum amount of energy for the corresponding v interval. Figure 3 shows the optimum design power level $A_{o\,opt}$, which is calculated according to the following relationship:

$$L_{ob} = A_{o\,opt} = \frac{W_{o\,max}}{dt\left(v_{W_{o\,max}}\right)}\ (\mathrm{kW/m^2}) \qquad (4)$$

The following numerical values for $A_{o\,opt}$ are obtained for the three stations mentioned above:

Altenwalde-Cuxhaven	0,377 kW/m²
Helgoland	0,70 kW/m²
Brocken	2,30 kW/m²

The yearly raw energies ΣW_o are:

Altenwalde-Cuxhaven	1285 kW/m² ·	y.
Helgoland	3390 kW/m² ·	y.
Brocken	10 600 kW/m² ·	y.

If it is also assumed that a wind generation station starts to deliver power at a raw power level of one tenth of the optimum design power level, that is at

$$L_{of} = 0.1\, A_{o\,opt}\ (kW/m^2) \qquad (4a)$$

the area segment between these limiting values L_{of} and L_{ob} under the L_o curve represents the specific raw wind energy which can be exploited by a wind generation station. This area is shown by vertical shading in Figure 3. It can also be seen that part of the raw wind power can be used which is greater than $A_{o\ opt}$. In the figure it is assumed that the installation can remain in operation up to twice the power level, that is for

$$L_{os} = 2\, A_{o\,opt}\ (kW/m^2) \qquad (4b)$$

but there is a downward adjustment of the design power level $A_{o\ opt}$. This part is also shown with vertical lines shading. The entire area with vertical shading below the L_o curve is the maximum exploitable raw wind energy under the conditions mentioned above.

The area with diagnonal shading are energy segments which cannot be exploited. We do not have to mention the fact that in /706 practice, the power levels or energies calculated in this way cannot be obtained. This is because the performance coefficient c_1 and the total efficiency η are smaller than one and, in addition, the public network requires that the generating plant is usually operated at a constant rotation rate. An installation controlled by the wind variations and subjected to constant rotation

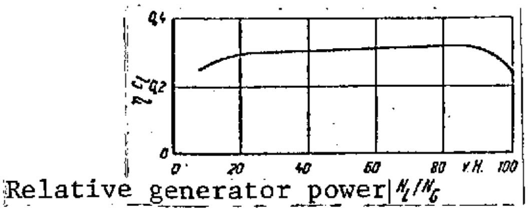


Figure 4. Dependence of ηc_1 on the relative generator power output for the 10 m Allgaier installation, Type D 8

rate results in additional losses. The purpose of the permanent level lines is only to show the method of analysis. The performance and energy characteristics for a specific wind generation station are obtained by considering the η- and the c_1 values and their variations as a function of wind velocity. These characteristics would run somewhat below the L_o or W_o characteristics, respectively. For clarity, these characteristics are not shown in Figure 3. This is best represented if the variation of ηc_1 of a wind generation station is known as a function of the percentage power level N_L, that is, the power level divided by the design power level of the generator N_G. Figure 4 shows this for the 10 m Allgaier installation.

It is appropriate to divide the permanent level lines into the following five regions:

1. The zero wind region.
   $v = 0$ to v_f $(m = 0$ to $0.1)$ * not exploitable

* m is the factor which must multiply $A_{t,opt}$ in order to obtain the power L_o for the corresponding region according to the assumptions above, i.e., $m = L_o/A_{t,opt}$.

2. The operational range proper
   $v = v_f$ to v_b $\quad$ ($m = 0.1$ to 1) $\quad$ exploitable

3. The operational range with control*
   $v = v_b$ to v_s $\quad$ ($m = 1$ to 2) $\quad$ exploitable

4. The path control region *
   $v = v_b$ to v_s $\quad$ ($m = 1$ to 2) $\quad$ not exploitable

5. The storm condition region
   $v = v_s$ to ∞ $\quad$ ($m = 2$ to ∞) $\quad$ not exploitable

II. CHARACTERISTIC VARIABLES

1. Optimum Raw Design Power Level $A_{o\ opt}$ and Maximum Raw Energy Exploitation Efficiency Σp_{max}

By dividing the permanent level lines into five regions, we obtain a few additional directives for the theoretical treatment of the wind variation. It is necessary to investigate a few characteristic variables and their variations. We have already become familiar with one of the variables, the specific raw design power level $A_{o\ opt}$. A second variable is called the maximum raw energy exploitation efficiency Σp_{max} and is defined as the ratio of the exploitable fractions (2. + 3.) in the five regions and the total raw wind energy.

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* The technical literature contains the term "sail condition" for this range, with the exploitable fraction (3) and the loss fraction (4).

The absolute and relative magnitudes of the energy contributions in the five regions mentioned above are the following:

1. "No wind"

$$(m = 0 \text{ to } 0.1) \qquad \Sigma W_{of} = \int_{o}^{v_f} L_o(v)\, dt(v) \qquad p_f = \frac{\Sigma W_{of}}{\Sigma W_o} \tag{5a}$$

2. "Operation"

$$(m - 0.1 \text{ to } 1) \qquad \Sigma W_{ob} = \int_{v_f}^{v_b} L_o(v)\, dt(v) \qquad p_b = \frac{\Sigma W_{ob}}{\Sigma W_o} \tag{5b}$$

3. "Operation with control"

$$(m = 1 \text{ to } 2) \qquad \Sigma W_{obr} = A_{o\ opt}\, \Sigma t(v) \Big|_{v_b}^{v_s} \qquad p_{br} = \frac{\Sigma W_{obr}}{\Sigma W_o} \tag{5c}$$

4. "Path control"

$$(m = 1 \text{ to } 2) \qquad \Sigma W_{owr} = \int_{v_b}^{v_s} L_o(v)\, dt(v) - \Sigma W_{obr} \qquad p_{wr} = \frac{\Sigma W_{owr}}{\Sigma W_o} \tag{5d}$$

5. "Storm conditions"

$$(m = 2 \text{ to } \infty) \qquad \Sigma W_{os} = \int_{v_s}^{\infty} L_o(v)\, dt(v) \qquad p_s = \frac{\Sigma W_{os}}{\Sigma W_o} \tag{5e}$$

The notation in the formulas given above is found from the definitions. The limiting wind velocities v_f, v_b, v_s are found from the magnitudes $L_o = m\, A_{o\ opt}$ according to the permanent level lines.

The energy contributions according to Figure 3 can be determined from the differences of the ordinate segments of the ΣW_o curve (corresponding to the L_o values). The maximum raw energy exploitation efficiency is obtained as follows from the definition

$$\Sigma p_{max} = \frac{\Sigma W_{ob} + \Sigma W_{obr}}{\Sigma W_o} = \frac{\Sigma W_{oa}}{\Sigma W_{oa} + \Sigma W_{on}}$$

where $\Sigma W_{oa} = \Sigma W_{ob} + \Sigma W_{obr}$ is the sum of the exploitable energy components (2. + 3.) and $\Sigma W_{on} = \Sigma W_{of} + \Sigma W_{owr} + \Sigma W_{os}$ is equal to the sum of the nonexploitable energy fractions (1. + 4. + 5.).

The numerical Table 1 shows the percentage energy contributions p for the three measurement stations with the above assumptions, for m = 0.1, 1 and 2, respectively. We find that each p contribution is about as large for the three stations, and therefore independent of v_m. The zero wind contributions p_f amount to between 3 to 5% of the total yearly energy. The operational contributions are about 40-50%, the operational contributions with control p_{br} are about 15%. The remainder of the nonexploitable energy contributions consist of p_{wr} or 8%, which corresponds to the "path control" and the contribution for the "storm conditions", with a considerable contribution p_s of about 30%. The maximum raw energy exploitation efficiency is therefore obtained as $\Sigma p_{max} =$ barely 60% $= \sim \Sigma_{r_{max}}$.

The contributions for the "path control" and for the "no wind conditions" are relatively small. This is why it does not make much sense to expand the assumed limits for m further upwards or downwards. It must only be determined whether it is technically possible to increase the design power level further above $A_{o\ opt}$, that is, further into the storm region, so that the considerable energy contribution could be exploited. For the Brocken area, the optimum design power level of 2.3 kW/m^2, corresponding to a wind velocity v_s = about 20 m/sec, is probably already above the technical limits at this time, which are about 10 m/sec at this time.*

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* In practice, the raw design power levels of existing installations are considerably lower. For example, for the 10-m Allgaier installation, $A_{o\,opt} = \frac{N_g}{F_R \cdot \eta_g} = \frac{8,8}{78,5 \cdot 0,23} = 0,5\ \mathrm{kW/m^2}$ at v_s = 8 m/sec and v_f = 3 m/sec. This installation is optimum for the station Altenwalde-Cuxhaven.

TABLE 1. WIND VARIABLES FOR MEASUREMENT STATIONS ALTENWALDE-CUXHAVEN, HELGOLAND AND BROCKEN (ONLY VALID FOR $m_l = 0.1$, $m_b = 1$, $m_s = 2$) *

Variable	Symbol	Unit	Altenwalde-Cuxhaven	Helgoland	Brocken
Height above nominal sea level	N_N	m	34	77	1164
Height above ground	H_G	m	19	21	28
Height above pertubation level	H_{ST}	m	4	10	28
Average wind velocity	v_m	m/s	4,37	6,66	10,12
Optimum raw power	$A_{o\ opt}$	kW/m²	0,33	0,71	2,3
Yearly raw energy	ΣW_o	kW/m², y	1285	3390	10600
1. "No wind" (m - 0 - 0.1)	$v = o - v_f$ *)	m/s	0—4,0	0—4,9	0—7,2
	P_f	%	[illegible],3	3,8	3,2
	r_f	%	47,0	40,5	39,5
2. "Operation" (m = 0.1 - 1)	$v = v_f - v_b$ *)	m/s	4,0—8,5	4,9—10,5	7,2—15,5
	P_b	%	48,6	40,8	42,7
	r_b	%	45,4	46,7	51,5
3. "Operation with control" (m = 1 - 2)	$v_{br} = v_b - v_s$ *)	m/s	8,5—10,6	10,5—13,3	15,5—19,5
	P_{br}	%	12,8	15,3	17,1
	r_{br}	%	5,0	8,3	9,0
4. "Path control" (m = 1 - 2)	$v_{or} = v_b - v_s$	m/s	8,5—10,6	10,5—13,3	15,5—19,5
	P_{or}	%	7,6	8,3	8,3
	r_{or}	%	5,0	8,3	9,0
5. "Storm" (m = 2 - 5)	$v = v_s - \infty$	m/s	10,6—∞	13,3—∞	19,5—∞
	P_s	%	25,5	31,7	28,7
	r_s	%	2,5	4,5	4,5
2. and 3. "Operation" and "Operation with control" (m = 0.1 - 2)	$v = v_b - v_s$	m/s	4,0—10,6	4,9—13,3	7,2—19,5
	ΣP_{max}	%	61,5	56,1	59,0
	Σr_{max}	%	55,0	60,5	60,5

* $m = L_o/A_{o\ opt}$, v_f Turn on wind velocity (start-up).
v_b - Operation velocity (at $A_{o\ opt}$)
v_s - Turn-off velocity (storm)
r - Percentage of yearly hours.

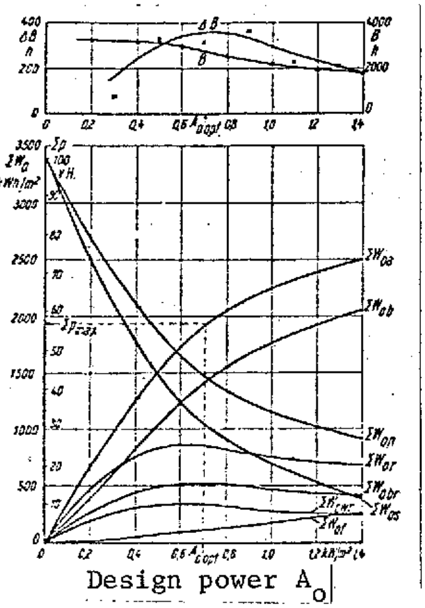


Figure 5. Variation of the energy contributions to ΣW_o according to Equations (5a) to (5e) for Helgoland (m = 0.1, m = 1 and m = 2)

Figure 5 (page 708) shows the variation of the energy contributions in the five regions on an absolute and relative scale for the measurement station Helgoland as a function of the design variable A_o and for the assumption m = 0.1, m = 1 and m = 2. This was done in order to determine whether the defined optimum design level is indeed an optimum for the exploitable energy. The figure was produced by measuring the area under the L_o curve for the individual regions and for the individual partial surfaces, and for various design variables A_o. This was done using a planimeter or by using the ΣW_o curves determined from the yearly permanent level lines plotted in a logarithmetic representation and not given here. It can be seen that the contributions ΣW_{obr} and ΣW_{owr} for "operation with control" and "path control", and therefore their sum, have a well defined maximum in the vicinity of $A_o = A_{o\ opt}$, the contributions are small on an absolute scale, which is why these maxima are not shown in the sum curves for ΣW_{oa} and ΣW_{on}, respectively. /707

The raw energy exploitation efficiency Σp can be obtained from a curve for ΣW_{oa} for each magnitude A_o.

The upper part of Figure 5 shows the duration of use B (in hours per year) = $\Sigma W_{oa}/A_o$ and its increment ΔB between the indicated measurement points of A_o. It is found that the increase ΔB does indeed have a maximum in the vicinity of $A_{o\ opt}$, i.e., the function $d\Delta B/dA_o$ for $A_o \sim A_{o\ opt}$. This is a point at which there is a relative minimum of A_o and also a relative maximum of the duration of use B, as a function of the unit power level A_o. Therefore there is also a maximum in the raw energy exploitation efficiency Σp, and in the exploitable yearly raw energy ΣW_{oa}. $A_{o\ opt}$ is therefore the true optimum design variable, given the assumptions for m made above (m_f = 0.1, m_b = 1, m_s = 2).

Figure 6 shows the raw energy exploitation efficiency Σp as a function of the power A_o referred to $A_{o\ opt}$, i.e. $\Sigma p = f(m_o) = f(A_o/A_{o\ opt})$ for the values from Figure 5 (Helgoland) and the corresponding values for Altenwalde-Cuxhaven and the Broken region and for the assumed conditions $(m_f = 0.1, m_b = 1, m_s = 2)$. For example for the 10-m Allgaier installation built in Helgoland we obtain a raw energy exploitation efficiency of about 42% with m_o = 0.45/0.70 = 0.64.

2. Theoretical Raw Design Power Level A_{oth} and Theoretical Yearly Raw Energy ΣW_{oth} as a Function of v_m.

It is known that there is a close relationship between the average wind velocity v_m and the raw wind power or the yearly raw wind energy level. It is natural to investigate this relationship. For this purpose, for 14 measurement stations contained in the "Data", those having the largest yearly raw wind energy, we calculated the quantities $A_{o\ opt}$ and ΣW_o mentioned above. Numerical Table 2 contains the results. Figure 7 shows this in a

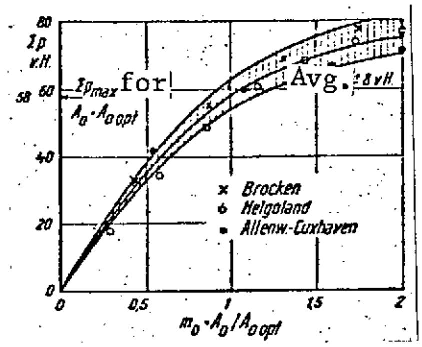


Figure 6. Dependence of the raw power efficiency Σp compared with relative degree of construction

$$m_o = A_o/A_{o\ opt}$$

graphical representation. The calculation is done according to the formulas given. It is found that, except for a large scatter in the measurement points shown with respect to the theoretical variation, there is a unique relationship between the average wind velocity v_m and the theoretical optimum specific raw design power level A_{oth}, that is the theoretical specific yearly raw wind energy ΣW_{oth} (only valid for m = 0.1, m = 1 and m = 2, according to the assumptions made above):

$$A_{o\,th} = 3{,}3 \cdot 10^{-3}\, v_m^{\,3}\, (kW/m^2) \pm 35\ v.H.$$
$$\Sigma W_{o\,th} = 11{,}6 \cdot v_m^{\,3}\, (kW/m^2 \cdot y.) \pm 14\ v.H.$$

There is no dependence on the average wind velocity v_m for the maximum raw energy efficiency Σp_{max} defined above, as was already found in numerical Table 1 and Figure 6. In general, with the assumptions made above (m = 0.1, m = 1 and m = 2) an optimum value of $\Sigma p_{max} \sim 0{,}60$ can be used [1]. In other words, in the best case about 60% of the yearly raw wind energy can be used. It is necessary to consider the fact that this value only applies if the short time fluctuations in the wind can be measured by the wind measuring devices by a "rapid response device".

TABLE 2. WIND VARIABLES FOR THE 14 FAVORABLE WIND STATIONS OF THE "DATA" (MAXIMUM YEARLY RAW ENERGY ΣW_o)

Measurement station	v_m	$L_{o\,th}$	$A_{o\,opt}$	ΣW_o	Σp_{max}	Σr_{max}	α	γ	v_b	v_b/v_m
1. Hamburg-Fuhlsbüttel	4,39	0,0520	0,455	1060	72,0	48,0	8,74	20200	9,05	2,06
2. Altw.-Cuxhaven	4,37	0,0513	0,377	1285	64,8	52,5	7,35	25050	8,50	1,95
3. Bremen-Freib.	5,34	0,0911	0,264	1455	53,4	72,0	2,90	15950	7,55	1,42
4. Nauen 31 m	5,46	0,0999	0,265	1590	50,8	70,0	2,65	15930	7,55	1,38
5. Brunsbüttelkoog	5,09	0,0804	0,350	1680	63,7	48,5	4,35	20900	8,30	1,64
6. Hohenpeissenberg	4,96	0,0704	0,685	1880	48,2	36,0	9,73	26700	10,60	2,18
7. Wyk a. Föhr	6,21	0,147	0,752	2770	61,1	56,0	5,12	18850	10,70	1,73
8. Quickborn 70 m	6,72	0,186	0,736	2610	53,7	76,5	3,97	14000	10,65	1,59
9. Wasserkuppe	5,96	0,131	0,945	2550	64,1	48,0	7,23	19500	11,53	1,93
10. Helgoland	6,66	0,181	0,713	3390	55,5	60,0	3,94	18750	10,51	1,58
11. Kahler Asten	7,17	0,226	0,934	3400	83,3	70,0	4,13	15050	11,49	1,60
12. Kalmit	7,08	0,217	0,934	3950	57,9	61,0	4,30	18220	11,49	1,63
13. Feldberg	8,11	0,333	2,245	6650	62,1	48,0	6,75	20000	15,41	1,90
14. Brocken	10,12	0,635	2,370	10600	58,7	62,5	3,74	16720	15,70	1,55
Avg. values					60,7	57,8	5,35	18980		1,73

$L_{o\,th} = 6{,}14 \cdot 10^{-4} \cdot v_m^3\ \mathrm{kW/m^2}$, $\alpha = \dfrac{A_{o\,opt}}{L_{o\,th}}$, $\gamma = \dfrac{\Sigma W_o}{L_{o\,th}}$,

$$v_b = \sqrt[3]{\frac{A_{o\,opt}}{6{,}14 \cdot 10^{-4}}}$$

/708

Since this cannot be done perfectly in practice, we could only hope to use a value of $\Sigma p_{max} \sim 0.50$.

Simple practical relationships are obtained with these values, so that the net characteristic variables of a specific wind generation station can easily be determined if the magnitude of the average wind velocity v_m is known for an erection site. For example, for a wind controlled installation, i.e., pitch rate $\lambda = u/v = \text{const}$), the optimum net design power level is $N = \eta\, c_l \cdot A_{o\,th} \cdot F_R$ (kW) and the maximum net yearly energy is $E = \eta\, c_l \cdot \Sigma p_{max} \cdot \Sigma W_{o\,th} \cdot F_R$ (kWh).

For a net-controlled installation (rotation rate n = const), these variables must be multiplied by the following working factor $\eta_R \approx 0.8$ to 0.9, which is the result of the constant rotation rate [1].

For completeness, Figure 8 also shows the magnitudes of the wind velocities of the individual regions v_f, v_b, v_s mentioned in

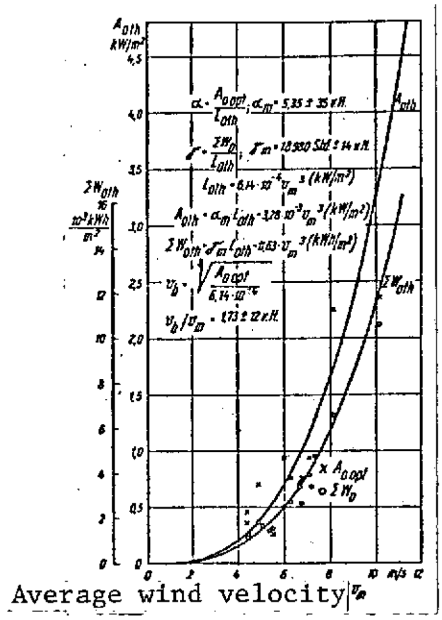


Figure 7. Dependence of the theoretical optimum raw design power $A_{o\ th}$ and the theoretical raw yearly energy ΣW_{oth} on the wind velocity v_m according to the numerical Table 2.

v_f- zero wind starting wind velocity, v_b- wind velocity for full design operational power, v_s- wind velocity for storm conditions (shut-down)

Equations (5a) to (5e) as a function of v_m assuming that m = 0.1, m = 1 and m = 2. It was calculated from the values in Table 2 for the 14 measurement stations. The theoretical linear functions are obtained as follows:

$$\left.\begin{aligned} v_{fth} &= 0{,}78\, v_m \pm 11\ \% \\ v_{bth} &= 1{,}68\, v_m \pm 11\ \% \\ v_{sth} &= 2{,}12\, v_m \pm 11\ \% \end{aligned}\right\} \text{ and}$$

SUMMARY

This report attempts to show how the unique picture of the raw energy contained to the wind can be obtained using the yearly permanent level lines. Also the power levels and their variations can be obtained. Using graphical procedures and

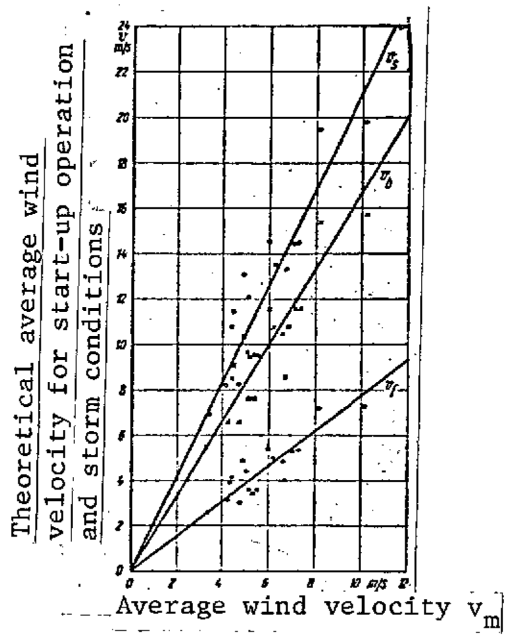


Figure 8. Dependence of the theoretical average wind velocity for start-up operation and storm conditions on the wind velocity v_m

numerical tables, the raw energy contained in the wind can be obtained for optimum exploitation conditions so that each wind generation station is matched to the erection site (wind location) by proper selection of the design level (generator size). In this investigation we wanted to demonstrate the method which follows after the yearly permanent level lines have been established. It would be desirable if wind generation plant designers would use this data to determine the design level and the associated limits after the average wind velocity of the erection site has been established.

APPENDIX

Methodology for Calculating the Economy of Generation Plants Driven by Wind (kWh - Net Costs)

The net cost of a kilowatt hour produced by a wind generation station can be calculated according to the formula

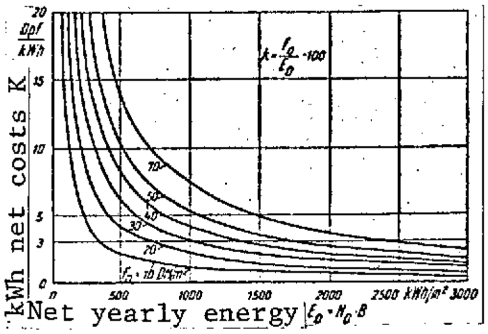


Figure 9. Dependence of the kWh net costs on the produced net yearly energy E_o for various specific yearly costs f_o.

/709

$$k = \frac{100 \cdot f_o}{N_o \cdot B} + c \text{ (Dpf/kWh)}$$

Here we have $f_o = z \cdot K_{ao}$, the fixed specific yearly costs of the installed power (in DM/m^2), if z is the yearly cost factor and K_{ao} is the specific installation costs, N_o the installed specific generator power (in kW/m^2), $B = E_o/N_o$ the operation period (in hours) where E_o = specific net yearly energy (in kWh/m^2) and c is the performance-dependent costs (in Dpf/kWh) (for wind generation plants practically equal to zero).

Figure 9 gives the quantity k in the function of the denominator of the formula given above, and f_o is the parameter (family of hyperbolas). The denominator $N_o \cdot B = E_o$ (kWh/m^2 years) is the specific yearly net power of a wind generation station assuming that the energy produced by the wind supply is completely exploited in the form of work and delivered to the connected network. Using the variables discussed above, we find the following optimum

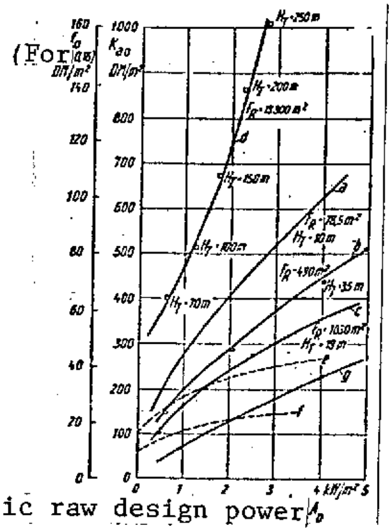


Figure 10. Dependence of specific construction costs K_{ao} and fixed yearly costs f_o for various installations on the specific net design power A_o

net values for a wind-controlled installation:* This defines all

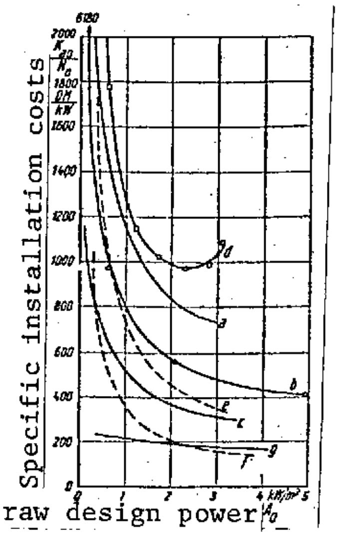
$$E_o = \Sigma W_o \cdot \Sigma p_{max} \cdot \eta_i c_i \quad \text{and} \quad N_o = A_{o\,opt} \cdot \eta_i c_i,$$

variables. Figure 9 shows an example. In order to obtain a net $k = 3$ Dpf/kWh for a yearly cost contribution of $f_o = 20$ DM/m², the net yearly energy E_o of the erection site must be at least 700 kWh/m². If it is assumed that $\Sigma p_{max} = 0.5$ and $\eta c_l = 0.3$ and that these are possible, then the wind location must have a raw yearly energy level of at least

$$\Sigma W_o = \frac{E_o}{\Sigma p_{max}\, \eta_i c_l} = \frac{700}{0.50 \cdot 0.3} = 4700 \text{ kWh/m}^2$$

According to Figure 7, this corresponds to $v_m = 7.5$ m/s ±11 percent, (North Sea Coast). For the case that f_o can be reduced to 10,

* For a net-controlled installation, E_o must be multiplied by the reduction factor $\eta_R = 0.8$ to 0.9.



a- 10-m Allgaier installation (F_R = 78.5 m², ηc_1 = 0.245) b- 25-m installation, dissertation U. Hütter, page 25 (F_R = 490 m², ηc_1 = 0.254), c- 100-kW project of the study association wind generation (F_R = 1030 m², ηc_1 = 0.318). d- Kleinhenz project (F_R = 13 300 m², ηc_1 = 0.381), e-f- theoretical costs for series production, 10-m Allgaier installation (e) and 100 kW project of the study association, (f), g- most economical installation according to Figure 9 (F_R = 2000 m², ηc_1 = 0.36). In installations b and d we have set 1 RM = 2 DM. HT tower height. In Figure 11: a to g, see caption for Figure 10.

Figure 11. Specific construction costs of various installations per unit of power as a function of specific raw design power A_o.

DM/m², the values would be:

$$E_o = 350 \text{ kWh/m}^2 \text{ and } \Sigma W_o = \frac{350}{0{,}15} = 2340 \text{ kWh/m}^2,$$

i.e., v_m = 5.8 m/sec (North German Flatland).

The specific installation costs K_{ao} or the specific yearly costs f_o for z = 0.16 are shown in Figure 10 as a function of A_o for a few installations. The power level dependence of K_{ao} was calculated assuming that the costs are increased by 50% when the design power level A_o is doubled. For clarity, we also show the dependence of the installation costs in DM/kW referred to the

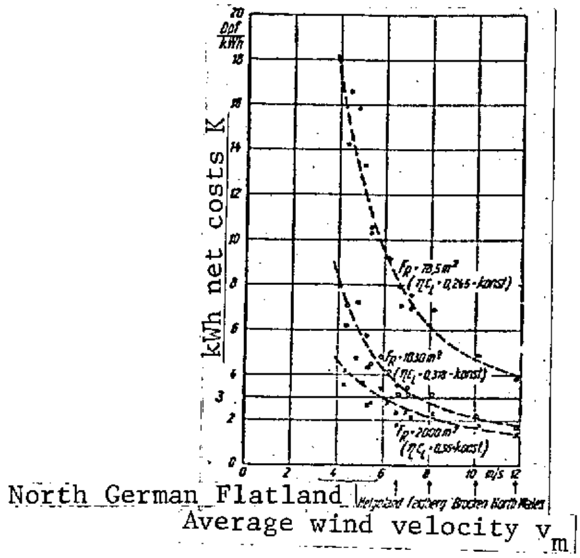


Figure 12. kWh net costs K is a function of average wind velocity v_m.

installed power level K_{ao}/N_o, which is usually done in the electrical power plant literature.

Figure 12 shows the net costs per kWh for the three different installations and for the 14 measurements installations given in the top of Table 2. The dashed curves were calculated using the formulas given above.

This representation concludes the methodology of the calculation. The absolute numbers for k are not intended to be correct, because the installation costs, K_{ao} and their dependence on A_o were partly estimated.

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Translated for National Aeronautics and Space Administration under contract No. NASw 2483, by SCITRAN, P. O. Box 5456, Santa Barbara, California, 93108.

STANDARD TITLE PAGE

1. Report No. NASA TT F-15,354	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle CHARACTERISTIC LINES (YEARLY PERMANENT LEVEL LINES) AND CHARACTERISTIC WIND VARIABLES FOR WIND ENERGY PRODUCTION		5. Report Date February, 1974
		6. Performing Organization Code
7. Author(s) Hans Pigge		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address SCITRAN Box 5456 Santa Barbara, CA 93108		11. Contract or Grant No. NASw-2483
		13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Translation of: "Kennlinien (Jahresdauerlinien) und Kenngrössen des Windes für die Windkraftnutzung". Elektrizitatswirtschaft, Vol. 54, No. 20, October, 1955, pp. 704-709.

16. Abstract

Optimum design methods for wind driven electrical generating plants are presented, based on yearly permanent wind level lines for selected erection sites. Wind conditions at any site are divided into five classes, of which only a few can be exploited by a given system. General purpose design curves are given.

17. Key Words (Selected by Author(s))	18. Distribution Statement Unclassified - Unlimited

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages ~~25~~ 26	22. Price 3.25